Anomalous ^{10}Be spikes during the Maunder Minimum: Possible evidence for extreme space weather in the heliosphere

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Received 11 July 2012; revised 28 September 2012; accepted 28 September 2012; published 8 November 2012.

[1] Extreme space weather conditions pose significant problems for standard space weather models, which are available for some limited realistic parameter ranges. As a good example, anomalous spikes of cosmic ray induced ^{10}Be have been found during the Maunder Minimum (AD1645–1715) at the qA negative solar minima, which cannot be quantitatively explained by standard drift theories of cosmic ray transport alone. Such an extreme amplification of solar cycle modulation of cosmic rays is presumably related to the altered condition of heliospheric environment at the prolonged sunspot disappearance, providing a clue for comprehensive understandings of long-term changes in heliospheric environment, solar cycle modulation of cosmic rays, and the maximal range of incident cosmic ray flux that is very important for our practical space activities. Model sophistication to achieve precise forecast of such extreme condition of the heliosphere and the incoming cosmic ray flux is also of urgent need as the Sun is currently showing a tendency toward lower activity. Here we show that the cosmic ray spikes found at the Maunder Minimum may be explained by the contribution from the cross-sector transport mechanism working in the heliosheath where cosmic ray particles effectively drift across stacked magnetic sectors due to the larger cyclotron radius than the distance between the sectors. Based on the new interpretation of the ^{10}Be record, we clarify potentially important problems for space weather modelers to help with more realistic modeling of the heliosphere during periods of extremely weak solar activity, such as the Maunder Minimum.

Citation: Kataoka, R., H. Miyahara, and F. Steinhilber (2012), Anomalous ^{10}Be spikes during the Maunder Minimum: Possible evidence for extreme space weather in the heliosphere, *Space Weather*, *10*, S11001, doi:10.1029/2012SW000835.

1. Introduction

[2] How do the extremely weak space weather conditions behave? Such a fundamental question about the extreme space weather conditions poses significant problems for standard space weather models, which are available for some limited realistic parameter ranges. The maximum sunspot number of solar cycle 24 is getting smaller than that of the previous cycle, and the possible rapid decrease in the cycle-averaged sunspot number may be indicative that we are about to enter another grand minimum in solar activity, a period of prolonged sunspot absence, for the next several decades [*Lockwood et al.*, 2011]. It is therefore important for both scientists and engineers to learn how extremely weak space weather conditions behave based on the observational records. The Maunder Minimum (AD1645–1715) is known as an extremely weak or grand minimum solar condition [*Eddy*, 1976]. The 11-year averaged intensity of the heliospheric magnetic field during the Maunder Minimum is estimated to have been about one third of present level, which resulted in about 10% increase in cosmic ray flux [*McCracken*, 2007], while the solar wind speed during the Maunder Minimum is estimated to have been 340 km/s, which is somewhat smaller than the present level [*Cliver et al.*, 1998]. In this paper we discuss the time profile of anomalous spikes of cosmic ray induced ^{10}Be occurred at the Maunder Minimum and its possible picture, as an extremely weak condition of the heliosphere to be challenged and clarified by realistic modeling. Such yearly

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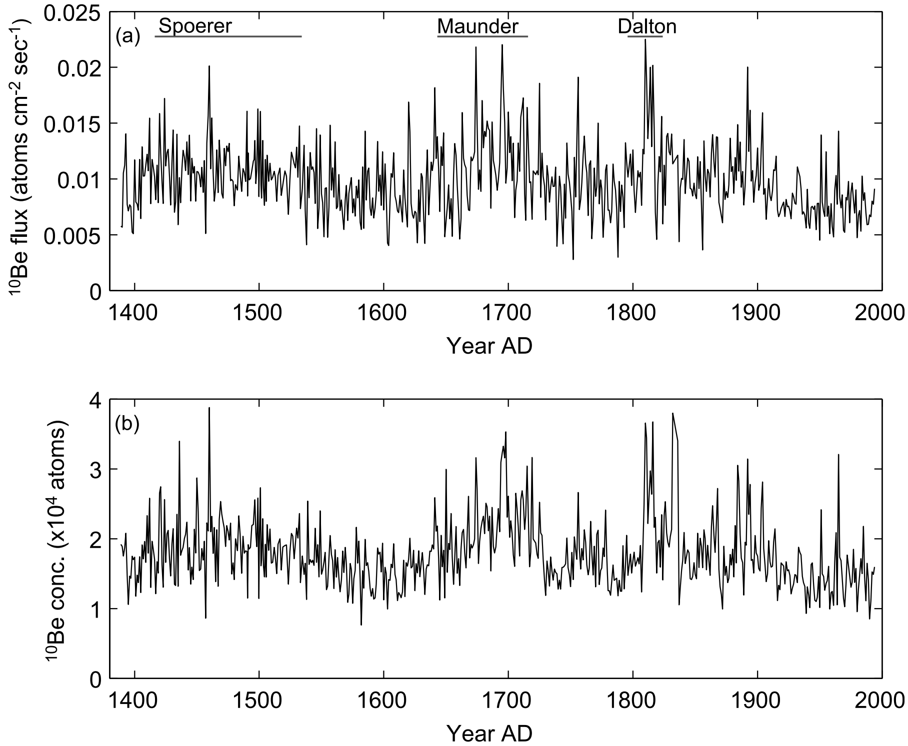

Figure 1. Time profiles of (a) ^{10}Be flux and (b) ^{10}Be concentration obtained from NGRIP ice core [*Berggren et al.*, 2009]. Indicated by horizontal bars are the periods of grand solar minima, i.e., Spoerer (AD1416–1534), Maunder (AD1645–1715), and Dalton (AD1795–1825) Minima.

scale enhancement of incident galactic cosmic rays can potentially increase operational risks of spacecraft and aircraft as well as manned space activities, and thus greater model sophistication is also needed in that context. In this paper we briefly describe the ^{10}Be spikes as possible evidence for cross-sector transport mechanism [*Florinski*, 2011; *Florinski et al.*, 2011].

2. Anomalous ^{10}Be Spikes in the Greenland Ice Core

[3] The cosmogenic isotope ^{10}Be in ice cores records past changes of cosmic rays incident to the Earth. The trajectory of cosmic rays in the heliosphere depends on the polarity and structure of the spirally winding magnetic field. Therefore, the obtained patterns of ^{10}Be provide the information on cyclic behaviors of the Sun and the heliosphere, such as the 11-year activity cycle, 22-year solar magnetic polarity (qA) reversals as well as the change in the large-scale current sheet structure of the heliosphere. Using a 600 year annual ^{10}Be record from NGRIP ice core, Greenland [*Berggren et al.*, 2009] (Figure 1a), the 22-year cycles in cosmic rays have been found to be amplified during the Maunder Minimum, as a possible result of altered large-scale structure of heliospheric current sheet [*Miyahara et al.*, 2009]. Associated with the amplified 22-year variation, large spikes were found at the solar cycle minima of negative solar magnetic polarity (qA negative phases) with a few tens of percent larger amplitudes compared to the qA positive phases, which may provide a very important clue to understand the least modulated cosmic ray spectrum. Similar spikes are also seen in the record, around the Spoerer and Dalton grand minima. We therefore hypothesize that such conditions are common in grand solar minima. We note that the effect of changing snow accumulation on ^{10}Be concentration (Figure 1b) has been corrected to obtain ^{10}Be flux (see the paper by *Berggren et al.* [2009]).

[4] Figure 2 shows the superposed time profiles of ^{10}Be flux for four qA negative and qA positive solar cycles around the Maunder Minimum. The record of ^{10}Be flux for AD1636–1739 were filtered to remove the long-term variations (>50 years), and were divided into eight solar cycles (four cycles for each polarity phase), based on the solar cycle reconstruction obtained with the record of ^{14}C data by *Stuiver et al.* [1998]. The time series have been overlaid each other so that the maxima of solar cycles (minima of ^{10}Be flux) are in synchronization. Annual-scale enhancements are seen in between the solar cycle maxima, but only at qA negative phase. The ages of the spikes are

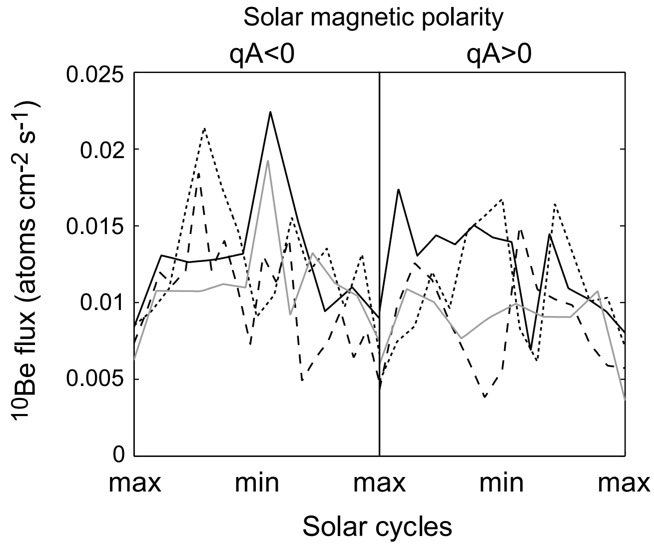

Figure 2. Time profiles of ^{10}Be flux [*Berggren et al.*, 2009] superposed for qA negative and qA positive solar cycles, around the Maunder Minimum. The record from AD1636 to AD1739 were divided into eight solar cycles (four cycles for each polarity phase), based on the solar cycle reconstruction with ^{14}C in tree rings. The periods of the four series, based on the NGRIP age model, are AD1636–1669 (dashed line), AD1669–1691 (solid line), AD1691–1719 (dotted line), and AD1719–1739 (gray line). Note that the plotted time series are tied each other only by solar cycle maxima. The ages of spikes at qA negative phases are AD1641, 1674, 1695, and 1725, respectively.

AD1641, 1674, 1695, and 1725, according to the NGRIP age model. Note that the dating error of this record is about a few years, and thus absolute ages of these events need be determined by further studies. The significance levels of these spikes are 2.7, 3.9, 3.9, and 2.8 times of the standard deviation of the whole record, respectively. The NGRIP age of the first event is consistent with the onset of the Maunder Minimum within the dating error. Most intense spikes have occurred in AD1674 and AD1695, while similar but smaller spike is also found in AD1725, which is one cycle after the end of the Maunder Minimum. We assume that this spike is suggesting that the heliosphere was still in the Maunder-minimum-like condition. The excesses of the ^{10}Be flux at qA negative phases to the mean of maximal fluxes of neighboring two qA positive cycles are 40%, 39% 26% and 39%, respectively. The mean duration between the spikes is 28 years. *Miyahara et al.* [2004] reported based on tree ring analyses that the 11-year cycles were extended to about 14 years during the Maunder Minimum. The above period of 28 years is therefore consistent with the Hale period during that time. Such periodic appearances of anomalous spikes are also suggested to provide a unique opportunity to better understand the solar-terrestrial connections, i.e., a possible link between the cosmic ray spikes and climate variations in the northern hemisphere [*Yamaguchi et al.*, 2010].

[5] Similar enhancement of ^{10}Be content for one to two years may also be produced by solar energetic particles [*Usoskin et al.*, 2006], nearby supernovae [*McCracken et al.*, 2004], climate influence on the ^{10}Be precipitation and accumulation at the NGRIP site, or errors in experimental procedures. However, these other possibilities are unlikely because of the cyclicity of the events (with Hale period), the dependence on solar magnetic polarity, and the fact that they occur close to the cycle minima of the Maunder Minimum. The ages of the spikes can be accurately determined with high precision measurements of ^{14}C in tree rings. Although the current sensitivity of ^{14}C measurements is not sufficient for detecting such annual scale spikes, superimposed ^{14}C data series show annual scale rapid enhancements as was attempted by *Yamaguchi et al.* [2010]. If not superimposed, the ^{14}C time series show noisy anomalies, but one of four spikes shown above is clearly detected in the tree ring of AD1726 (corresponding to the GCR flux anomaly in AD1725) as shown in Figure 3. The statistical significance of this spike is more than three times the measurement error. Enhancement with similar amplitude is also seen in ^{14}C around AD1671–1673 (corresponding to GCR enhancement in AD1670–1672); although it is double peaked and thus needs further precise measurements. The age of this enhancement is consistent with the ^{10}Be spike in AD 1674 within the dating error of the ice core.

[6] We would like to note that not all of the anomalous spikes found in NGRIP record are seen in ^{10}Be data from the Dye-3 ice core [*Beer et al.*, 1998; *Berggren et al.*, 2009]

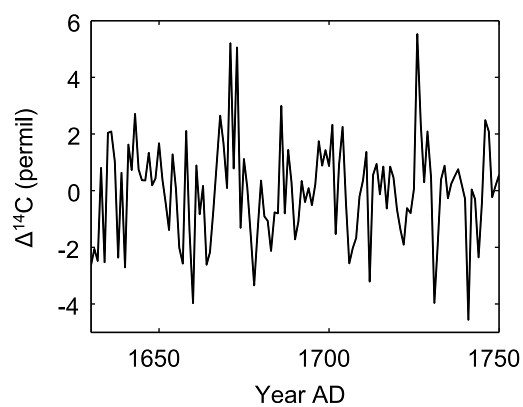

Figure 3. High-pass filtered ^{14}C record obtained by *Stuiver et al.* [1998] as subtracted from the 30 year running average. Two anomalies are seen around AD1671–1673 and AD1726, although the former anomalies are double peaked. The latter peak in AD1726 determines the age of GCR enhancement to be AD1725. This time lag is due to the circulation of ^{14}C in the carbon cycle. Note that the time lag depends on the variation time scale, and it is one year in the case of annual-scale change [*Siegenthaler and Beer*, 1988].

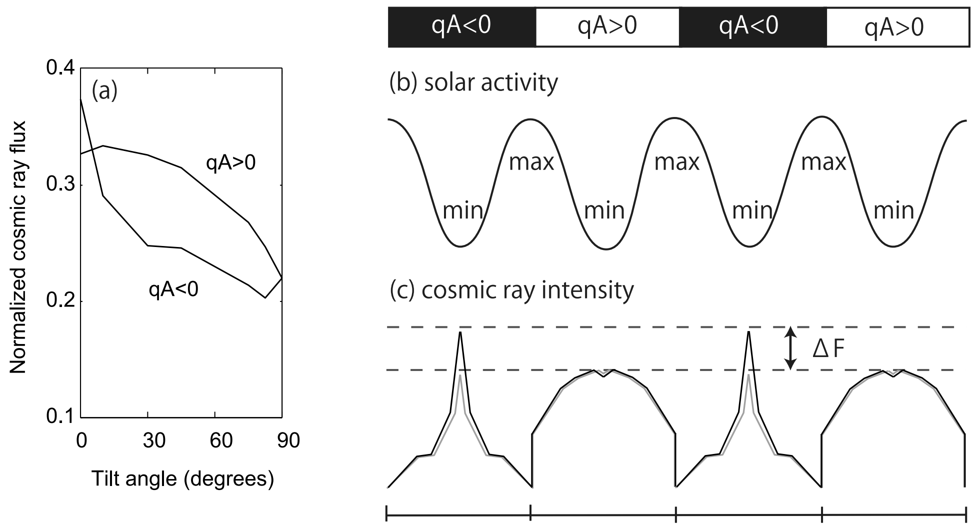

Figure 4. A schematic illustration summarizing the theoretically suggested time profile of incident cosmic rays at the Earth. (a) Incident cosmic rays at the Earth calculated based on standard drift theory for qA > 0 and qA < 0 phases as a function of the tilt angle of heliospheric current sheet [*Kota and Jokipii*, 2001]. (b) Solar activity cycles and (c) the predicted time profile of incident cosmic rays where black line is for the case when the tilt angle reached to 0 degrees at solar cycle minima and to 75 degrees at cycle maxima, while gray line is for the case when the tilt angle reaches only to 5 degrees at cycle minima, which is usual for present observational era. The anomaly ΔF (ratio of maximal flux at qA < 0 to maximal flux at qA > 0) as predicted by standard drift theories is about 15–20%, whereas the observed one in ^{10}Be flux is about 30–40%.

(see *Berggren et al.* [2009, Figure 1] for the detailed comparison between the NGRIP and Dye-3 ^{10}Be records). The spikes detected in NGRIP data are overall less pronounced in Dye-3 record, although some are seen e.g., around AD1697. The discrepancies between these two records may be due to the sampling resolution of Dye-3 record. The ice samples of Dye-3 were obtained from the cores annually after/above AD1777 based on the annual layer counting of H_2O_2, while it was sampled equidistantly before/below AD1777. It may cause the attenuation of annual-scale enhancement. Discrepancies of ^{10}Be flux from different ice cores can also result from the differences in the location of sampling, such as geomagnetic latitude and altitude, and the accumulation rate of snow at the location of sampling, and the dating of cores. It is also possible that annual-scale spike in the record of concentration is lost in the record of flux calculated based on the accumulation rate. It can happen, for example, at years when snow accumulation was artificially low due to the post depositional removal by ablation.

[7] It has been theoretically suggested that cosmic rays drift inward along the current sheet and upward to the polar region at qA < 0, while the paths are inverted at qA > 0 [*Jokipii and Thomas*, 1981]. As shown in Figure 4, the standard drift theories can reproduce a certain degree of rapid enhancement of ^{10}Be content at solar minimum of qA negative phase against that of qA positive phase [*Kota and Jokipii*, 2001], given that the tilt angle of the heliospheric current sheet reaches to nearly zero degrees. This effect can account for 15–20% enhancement, which is about a half of the spike amplitude of 30–40% as observed in the ice core.

3. Cross-Sector Transport of Cosmic Rays in the Heliosheath

[8] Based on recent observational data with the Voyager spacecraft in the qA negative phase, a new transport mechanism of cosmic rays is suggested to be working in the distant heliosheath where cosmic ray particles effectively drift across stacked magnetic sectors (Figure 5) due to the larger cyclotron radius compared to the distance between the sectors [*Florinski*, 2011; *Florinski et al.*, 2011].

[9] Extending the new cross-sector mechanism, we examine the possible modulation amplitude of cosmic ray proton flux in the heliosheath. In the heliosheath, a simple compression of a magnetohydrodynamic fluid gives the flow speed $u \propto r^{-2}$ and then the associated azimuthal magnetic field amplitude $B \propto r$, so that the ratio of a particle's cyclotron radius to the average width of a sector increases as the heliocentric distance r. When the sector spacing becomes comparable to the gyroradii, these particles acquire a certain degree of mobility across the stack of magnetic sectors. The gyro radii of 0.1 and 1.0 GeV protons in 0.1 nT magnetic field are 0.1 AU and 0.38 AU, respectively. In such a present situation, the gyro radii of sub-GeV protons are usually smaller than a typical sector distance of 0.8 AU in the heliosheath, and the cross-sector transport does not work effectively. Presumably very weak magnetic

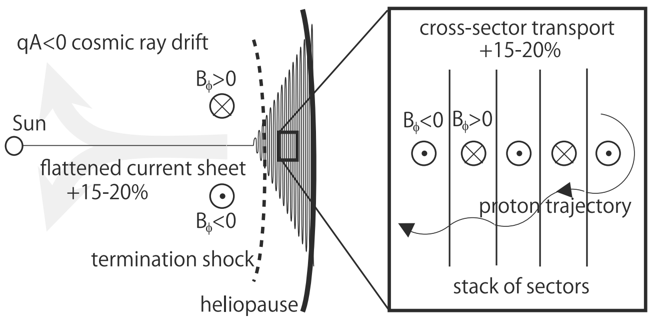

Figure 5. Vertical cross-sectional view of the heliosphere. The termination shock and heliopause are shown with a dashed curve and solid curve, respectively. The percentages given are the increase in cosmic ray intensity during the solar minimum of qA negative phase against that of qA positive (the magnetic field directions and the cosmic ray paths indicated by gray arrows are for qA < 0 phase). The cross-sector transport in the heliosphere can give additional 15–20% increase, while the flattened current sheet gives 15–20% increase during the qA negative phase.

field during the Maunder Minimum [*Steinhilber et al.*, 2010] therefore provides an excellent condition for invoking the cross-sector mechanism for the whole sub-GeV cosmic rays to enhance the ^{10}Be production. We further assume that cosmic rays observed at the Earth are very sensitive to this effect only during the qA negative phase when they drift inward along the equatorial current sheet.

[10] According to the result of *Florinski et al.* [2011], the cross-sector diffusion coefficient in the heliosheath is approximately proportional to r, $\kappa_{xx} \propto r$, while the simulated diffusion coefficient as used for the standard drift theory may be approximated as $\kappa_{xx} \propto r^{-2}$ [e.g., *Florinski et al.*, 2003]. The modulation amplitude in the heliosheath is then estimated from the simplest one-dimensional diffusion as $\exp\left(-\int_{X_{TS}}^{X_{HP}} \frac{u}{\kappa_{XX}} dX\right)$, where X_{HP} and X_{TS} are the radial distance of the heliopause and heliosheath from the Sun, respectively, and we assume $u \propto r^{-2}$. The modulation amplitude during the cross-sector situation of $\kappa_{xx} \propto r$ as opposed to the standard situation of $\kappa_{xx} \propto r^{-2}$ therefore only depends on the distance ratio between X_{HP} and X_{TS}. This accounts for 15–20% increase in the cosmic ray flux, assuming $X_{HP}/X_{TS} = 1.4$. The ratio of 1.4 is a nominal value as supported by a number of heliospheric simulations [e.g., *Müller et al.*, 2006]. The 15–20% increase due to the cross-sector mechanism plus further 15–20% increase in the qA negative phase as expected from drift theories with flattened heliospheric current sheet pattern is comparable with the observed 30–40% spike amplitude.

[11] It is therefore suggested that the anomalous ^{10}Be spike at the cycle minima of qA negative phase found at the Maunder Minimum is a possible result of the least modulated situation when both the flattened current sheet effect inside the termination shock [*Kota and Jokipii*, 2001] and the cross-sector effect in the heliosheath [*Florinski et al.*, 2011] work together to enhance the cosmic ray flux at the Earth, which does not likely occur except for extremely weakened solar activity. We note at such cycle minima the magnetic sectors still remain in the heliosheath from the previous year while the current sheet inside the termination shock is flattened as shown in Figure 5. The above discussion is, however, based on the extrapolation of our current understanding of heliospheric structure to the Maunder minimum. Much improvement of the understanding of the heliospheric structure is needed to validate the above explanation. Especially, it would be important to investigate the accumulation pattern of the heliospheric current sheet in the heliosheath. We also note that ^{10}Be spikes may cause underestimation of solar activities and the related parameters for the grand minima reconstructed from ^{10}Be, such as total solar irradiance, if the additional flux of cosmic rays due to the drift effect and cross-sector effect is not taken into account. The solar cycle average of ^{10}Be flux amounts to a 3–4% higher value than without the spikes for qA < 0.

4. Summary

[12] We showed that the cross-sector transport mechanism may be important to be modeled, in addition to the standard drift mechanism, to understand the realistic space weather during extremely weak solar activity, such as the Maunder Minimum. The quantitative modeling of anomalous spikes is important to understand the modulation mechanisms of cosmic rays and therefore contributes to validation of the current heliospheric simulation. It is also useful for future space weather applications to mitigate potential risks of spacecraft and aircraft operations and radiation doses to the astronauts and aircraft crews. Since the accumulation of the magnetic field in the heliosheath plays an important role, the time variation across the solar minimum of the grand minima is an interesting topic to be investigated in more detail. Some other important topics include the self-consistent modeling of solar corona, which will tell us the number density and speed of the solar wind as well as the magnetic field strength. Such parameters are fundamental to understand the heliospheric size and the absolute value of cosmic ray flux incident to the Earth, although the occurrence pattern of anomalous spikes during only qA negative phase cannot be explained by the fundamental parameters alone. The exact treatment of cosmic ray transport in the vicinity of a realistic current sheet would also be important for better quantitative estimation of the contribution of flattened current sheet to the spiky enhancements.

[13] **Acknowledgments.** We thank A.-M. Berggren and J. Beer for providing the ^{10}Be data from NGRIP and Dye-3, respectively. We thank H. Washimi, J. Kota and R. Jokipii for their fruitful comments. H.M.'s work has been supported by a grant from the Japan Society for the Promotion of Science. F. S. acknowledges financial support by NCCR climate – Swiss climate research and by the Swiss National Science Foundation under grant CRSI122-130642(FUPSOL).

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